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Voltage unbalance assessment in secondary radial distribution networks with single-phase photovoltaic systems

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ABSTRACT

This research describes a way to analyze voltage unbalance sensitivity for different maximum sizes of a single-phase photovoltaic system (SPPVS) with multiple PV penetration levels in a typical secondary radial distribution network (SRDN) in Spain. This analysis effectively assesses current requirements as specified in regulations concerning maximum size to be connected. It thus helps distribution network operators to define optimal limits, depending on their context. A stochastic assessment method is proposed to account for any random combination of SPPVSs in an SRDN. In addition, this method evaluates weekly voltage unbalance during a one-year time period, on the basis of 10-min intervals. More specifically, the voltage unbalance in SRDNs with SPPVSs is assessed for each 10-min interval by means of a probabilistic radial three-phase load flow (RTPLF). The results obtained show the maximum sizes of the SPPVS to be connected as a function of the PV penetration level in the SRDN, where high PV penetrations can produce voltage unbalance problems.

Introduction

Nowadays, the scientific community is involved into an intense investigation to find new photovoltaic devices (third generation PV technology) which provide low-cost solar electricity. These devices are composed of materials characterized by low preparation cost, minimum environmental impact, light weight and wide availability [1–6]. The performances of many of these devices are lower than those of silicon cells, however the trade-off between energy generated and invested capital can be profitable.

Several countries have reached the PV grid parity as the levelised cost of electricity for the PV technology in these countries can be compared with their local retail electricity prices in a competitive way. In most of the cases, this parity has been reached without any current subsidy or feed-in tariff incentive, but it has also been necessary a favourable regulatory framework, through net-metering or self-consumption laws [7,8]. The grid parity paradigm is possible in the rest of the world, but future research works are required in the smart grid research to mature this outcome [9,10].

The integration of high PV penetration levels in low voltage radial distribution networks can cause inadmissible voltage unbalances [11–14]. In order to minimize this problem as well as other adverse impacts, there are various technical regulations for the interconnection of PV systems [15]. These connection requirements are based on a deterministic analysis. However, this type of analysis has the disadvantage of not being able to objectively specify the location where the voltage unbalance in a secondary radial distribution network (SRDN) could surpass the standard limit during a given time interval. Furthermore, it is also incapable of determining the frequency of such an event. The reason for this lies in the fact that the variables in an SRDN with PV systems are subject to uncertainties stemming from the inherent randomness of PV power outputs and loads. Therefore, probabilistic techniques are the tools that can best assess the impact of uncertainty on SRDN variables. Among all these techniques, the most frequently used are probabilistic load flow based on Monte Carlo simulation, analytical methods, and approximation methods.

Although analytical methods are computationally more effective than Monte Carlo simulations, they must be based on certain mathematical assumptions. Firstly, it is necessary to define linear models to handle the nonlinearities of the balanced power system, either for meshed [16] or radial [17,18] configurations. Then, convolution techniques must be implemented to obtain the uncertainty of random outputs [16–19]. Finally, Gram–Charlier [17,19] or Cornish–Fisher [16,18] expansions estimate the probability functions of random outputs.

An example of an approximation method is the point-estimate method (PEM), which directly provides the first statistical moments

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of random outputs based on only a few deterministic load flows. Gram–Charlier or Cornish–Fisher expansions are then used to characterize random outputs. The first PEM in [20] was subsequently followed by new and improved versions. In fact, this research study used one of the schemes of Hong's PEM [21]. The number of deterministic simulations performed (e.g. $K^{*}m$ or $K^{*}m + 1$) grows linearly with the number of input random variables (m) and the scheme selected ($K = 2, 3, 4$). According to [22,23], the $2m + 1$ scheme provides the best performance for a high number of random inputs. Although reference [22] focuses on deterministic balanced load flows and reference [23] focuses on deterministic three-phase load flows, both studies only consider meshed configurations [24].

In the context of four-wire SRDNs, phase domain analysis is necessary, not only for incorporating the load unbalance and line impedance asymmetries, but also to assess the impact of single-phase photovoltaic systems (SPPVSs). The contribution of this paper is the use of Hong's PEM ($2m + 1$ scheme) [22,23] to solve the probabilistic three-phase power flow problem in radial configurations. The use of a specific radial load flow (e.g. [25]) is mandatory in radial configurations since the conventional load flow [24] gives convergence problems. This PEM for radial configurations is then combined with the Cornish–Fisher expansion. The advantages of this tool for the assessment of the impact of SPPVSs on SRDNs are the following:

- This PEM uses deterministic routines, but has a lower simulation cost than that of the Monte Carlo simulation.
- The simulation cost of this PEM is only slightly higher than the cost of the analytical method based on convolution techniques. However, when the analytical method is applied to unbalanced power systems and radial configurations, its computational cost is much higher than that of the PEM.
- The Cornish–Fisher expansion used in our study performs better for non-Gaussian PV random variables [18].

Aim of the study

Voltage unbalance [26] is a growing power quality concern in SRDNs with SPPVSs because of their variable size and location [11,12,27–31]. Such PV systems are currently being connected on the basis of the "fit and inform" principle, which mainly depends on the perspectives and financial conditions of homeowners. Within this context, even if the voltage unbalance in an SRDN without PV is within standard limits, there is no guarantee that it will remain so. Therefore, the number of admissible SPPVSs or their maximum size in SRDNs must be analyzed in such a way as to keep the voltage unbalance within standard limits.

Currently, the connection of SPPVSs in SRDNs is subject to requirements regarding maximum size (power). The objective of such regulations is to limit voltage unbalance. In most national regulations, this limit is approximately 5 kVA: 3 kW in the Endesa Utility Company [32]; 3.4 kVA in the UK [33]; 4.6 kVA in Austria and Germany [33]; 5 kW in Spain [34]; and 6.6 kW in Italy [35]. However, in Norway and France [33], the limit is much higher (15 kVA and 18 kVA, respectively).

This difference in standards indicates that the impact of variables such as the type of SRDN and PV penetration level is in urgent need of clarification. This knowledge will help distribution network operators to define optimal limits for specific scenarios. In our study, this information was obtained by means of a voltage unbalance sensitivity analysis in an SRDN of the maximum size of SPPVS and of the PV penetration level. PV penetration is defined as follows:

$$\text{PV penetration} = \frac{\text{Annual PV capacity factor} * \text{Installed PV power}}{\text{Maximum SRDN power}} \tag{1}$$

where the annual PV capacity factor is the ratio of annually produced energy to the energy that could have been produced if the PV had operated continuously at full power.

A stochastic assessment method was used to account for any random combination of SPPVSs in an SRDN. In addition, this method can be used to evaluate the voltage unbalance in a one-year time period, for 10-min intervals, according to regulations [36,37]. More specifically, the voltage unbalance in SRDNs with SPPVSs is assessed by a probabilistic radial three-phase load flow (RTPLF).

Voltage unbalance

Voltage unbalance can be characterized by different variables [38]. Generally addressed is the ratio of the fundamental negative-sequence component ($\vec{U}^2$) to the fundamental positive-sequence component ($\vec{U}^1$). Therefore, the voltage unbalance factor (VUF) is defined as $\xi = |\vec{U}^2/\vec{U}^1|$.

Voltage unbalance is time-variant in power systems. In this scenario, the use of indices is the most useful way of reducing the voltage unbalance to a single number [38]. Although the PV systems can influence the unbalance levels of all the nodes of a radial distribution network [11,12], the use of a site index is preferred [39,40]. This site index is obtained from a certain percentile (e.g. 95th, 99th) of the statistical characterization (cumulative distribution function or CDF) of the measurements of voltage unbalance over a long observation period (e.g. a one-day or one-week period) with a given time average (e.g. 3-s or 10-min interval). The most commonly used voltage unbalance index is the 95th weekly percentile of the variable $\xi_{,10\text{-min}}$ (VUF based on a 10-min mean), i.e., $\xi_{,10\text{-min},95w}$ [38].

As voltage unbalance can have various adverse effects [41], the allowable compatibility level in low voltage supply systems is usually limited to 2% [36]. In the same context, different regulations, utility guidelines, and international standards suggest allowable planning/compatibility levels in the 1–5% interval: 1.3% in the UK [33]; 2% in France, Germany [33], and the EU [37]; and 2–2.5% in IEEE standard [42]. In this paper, a 2% limit is assumed for the site index 95th weekly percentile of the variable 10-min VUF at any kth SRDN node ($\xi_{k,10\text{-min}}$), i.e., $\xi_{k,10\text{-min},95w}$.

Probabilistic PV and load model

Probabilistic PV system model

The probabilistic PV system model in [18] is specified for a 10-min interval. It provides information regarding the marginal distribution (probability density function [PDF] and cumulative distribution function [CDF]) of the PV random power for each ith 10-min interval, mth month, and jth SRDN node $u_{j,10\text{-min}_i}(m)$. Thus, the random variables hourly diffuse fractions and daily clearness index are used to build $u_{j,10\text{-min}_i}(m)$. Furthermore, this model accounts for the stochastic interdependence of the PV distributions corresponding to close locations (nodes) due to similar meteorological conditions [43]. This dependence is modelled separately from marginal distributions with a specific rank correlation matrix [18]. The model generates dependent PV power outputs based on multivariate dependent random numbers [18].

Probabilistic load model

Currently, certain distribution network operators are involved in the massive deployment of smart meters in the SRDNs to measure electrical load. This makes it possible to statistically characterize the load at each node by using measurements obtained and